

AN ELECTROSTATIC FLUID ACCELERATOR FOR AND A METHOD OF CONTROLLING FLUID FLOW

Related Applications

[0001] The patents entitled ELECTROSTATIC FLUID ACCELERATOR, serial no. 09/419,720, filed October 14, 1999; METHOD OF AND APPARATUS FOR ELECTROSTATIC FLUID ACCELERATION CONTROL OF A FLUID FLOW, serial no. _____, filed June 21, 2002, (attorney docket no. 432.004); and AN ELECTROSTATIC FLUID ACCELERATOR FOR AND A METHOD OF CONTROLLING FLUID FLOW, serial no. _____ filed _____ (attorney docket no. 432.005), all of which are incorporated herein in their entireties by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The invention relates to a device for and method of accelerating, and thereby imparting velocity and momentum to a fluid, and particularly to the use of corona discharge technology to generate ions and electrical fields especially through the use of ions and electrical fields for the movement and control of fluids such as air.

Description of the Related Art

[0003] A number of patents (*see, e.g.*, U.S. Patent Nos. 4,210,847 by Shannon, et al. and 4,231,766 by Spurgin) describe ion generation using an electrode (termed the “corona electrode”), attracting and, therefore, accelerating the ions toward

another electrode (termed the “collecting” and/or “attracting” electrode), thereby imparting momentum to the ions in a direction toward the attracting electrode.

Collisions between the ions and the fluid, such as surrounding air molecules, transfer the momentum of the ions to the fluid inducing a corresponding movement of the fluid.

[0004] U.S. Patent Nos. 4,789,801 of Lee, 5,667,564 of Weinberg, 6,176,977 of Taylor, et al., and 4,643,745 of Sakakibara, et al. also describe air movement devices that accelerate air using an electrostatic field. Air velocity achieved in these devices is very low and is not practical for commercial or industrial applications.

[0005] U.S. Patent Nos. 3,699,387 and 3,751,715 of Edwards describe the use of multiple stages of Electrostatic Air Accelerators (EFA) placed in succession to enhance air flow. These devices use a conductive mesh as an attracting (collecting) electrode, the mesh separating neighboring corona electrodes. The mesh presents a significant air resistance and impairs air flow thereby preventing the EFA from attaining desirable higher flow rates.

[0006] Unfortunately, none of these devices are able to produce a commercially viable amount of the airflow. Providing multiple stages of conventional air movement devices cannot, in and of itself, provide a solution. For example, five serial stages of electrostatic fluid accelerators placed in succession deliver only a 17% greater airflow than one stage alone. *See*, for example, U.S. Patent No. 4,231,766 of Spurgin.

[0007] Accordingly, a need exists for a practical electrostatic fluid accelerator capable of producing commercially useful flow rates.

SUMMARY OF THE INVENTION

[0008] The invention addresses several deficiencies in the prior art limitations on air flow and general inability to attain theoretical optimal performance. One of these deficiencies includes excessive size requirements for multi-stage EFA devices since several stages of EFA, placed in succession, require substantial length along an air duct (*i.e.*, along air flow direction). This lengthy duct further presents greater resistance to air flow.

[0009] Still other problems arise when stages are placed close to each. Reduced spacing between stages may produce a “back corona” between an attractor electrode of one stage and a corona discharge electrode of an adjacent next stage that results in a reversed air flow. Moreover, due to the electrical capacitance between the neighboring stages, there is a parasitic current flow between neighboring stages. This current is caused by non-synchronous high voltage ripples or high voltage pulses between neighboring stages.

[0010] Still another problem develops using large or multiple stages so that each separate (or groups of) stage(s) is provided with its own high voltage power supply (HVPS). In this case, the high voltage required to create the corona discharge may lead to an unacceptable level of sparks being generated between the electrodes. When a spark is generated, the HVPS must completely shut down for some period of time required for deionization and spark quenching prior to resuming operation. As the number of electrodes increases, sparks are generated more frequently than with one set of electrodes. If one HVPS feeds several sets of electrodes (*i.e.*, several stages) then it will be necessary to shut down more frequently to extinguish the

increased number of sparks generated. That leads to an undesirable increase in power interruption for the system as a whole. To address this problem, it may be beneficial to feed each stage from its own dedicated HVPS. However, using separate HVPS requires that consecutive stages be more widely spaced to avoid undesirable electrical interactions caused by stray capacitance between the electrodes of neighboring stages and to avoid production of a back corona.

[0011] The present invention represents an innovative solution to increase airflow by closely spacing EFA stages while minimizing or avoiding the introduction of undesired effects. The invention implements a combination of electrode geometry, mutual location and the electric voltage applied to the electrodes to provide enhanced performance.

[0012] According to an embodiment of the invention, a plurality of corona electrodes and collecting electrodes are positioned parallel to each other or extending between respective planes perpendicular to an airflow direction. All the electrodes of neighboring stages are parallel to each other, with all the electrodes of the same kind (*i.e.*, corona discharge electrodes or collecting electrodes) placed in the same parallel planes that are orthogonal to the planes where electrodes of the same kind or electrodes edges are located. According to another feature, stages are closely spaced to avoid or minimize any corona discharge between the electrodes of neighboring stages. If the closest spacing between adjacent electrodes is “a”, the ratio of potential differences $(V1 - V2)$ between a voltage $V1$ applied to the first electrode and a voltage $V2$ applied to the closest second electrode, and the distance between the electrodes is a normalized distance “a_N”, then $a_N = (V1 - V2)/a$. The normalized distance between the corona discharge wire of one stage to the closest part of the

neighboring stage should exceed the corona onset voltage applied between these electrodes, which, in practice, means that it should be no less than 1.2 to 2.0 times of the normalized distance from the corona discharge to the corresponding associated (*i.e.*, nearest) attracting electrode(s) in order to prevent creation of a back corona.

[0013] Finally, voltages applied to neighboring stages should be synchronized and syn-phased. That is, a.c. components of the voltages applied to the electrodes of neighboring stages should rise and fall simultaneously and have substantially the same waveform and magnitude and/or amplitude.

[0014] The present invention increases EFA electrode density (typically measured in stages-per-unit-length) and eliminates or significantly decreases stray currents between the electrodes. At the same time, the invention eliminates corona discharge between electrodes of neighboring stages (*e.g.*, back corona). This is accomplished, in part, by powering neighboring EFA stages with substantially the same voltage waveform, *i.e.*, the potentials on the neighboring electrodes have the same or very similar alternating components so as to eliminate or reduce any a.c. differential voltage between stages. Operating in such a synchronous manner between stages, electrical potential differences between neighboring electrodes of adjacent EFA components remains constant and any resultant stray current from one electrode to another is minimized or completely avoided. Synchronization may be implemented by different means, but most easily by powering neighboring EFA components with respective synchronous and syn-phased voltages from corresponding power supplies, or with power supplies synchronized to provide similar amplitude a.c. components of the respective applied voltages. This may be achieved with the same power supply connected to neighboring EFA components or with different, preferably matched

power supplies that produce synchronous and syn-phased a.c. component of the applied voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Figure 1A is a schematic diagram of an Electrostatic Fluid Accelerator (EFA) assembly with a single high voltage power supply feeding adjacent corona discharge stages;

[0016] Figure 1B is a schematic diagram of an EFA assembly with a pair of synchronized power supplies feeding respective adjacent corona discharge stages;

[0017] Figure 2A is a timing diagram of voltages and currents between electrodes of neighboring EPA stages with no a.c. differential voltage component between the stages;

[0018] Figure 2B is a timing diagram of voltages and currents between electrodes of neighboring EFA stages where a small voltage ripple exists between stages;

[0019] Figure 3 is a schematic diagram of a power supply unit including a pair of high voltage power supply subassemblies having synchronized output voltages;

[0020] Figure 4A is a schematic top view of a two stage EFA assembly implementing a first electrode placement geometry; and

[0021] Figure 4B is a schematic top view of a two stage EFA assembly implementing a second electrode placement geometry.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0022] Figure 1A is a schematic diagram of an Electrostatic Fluid Accelerator (EFA) device 100 comprising two EFA stages 114 and 115. First EFA stage 114 includes corona discharge electrode 106 and associated accelerating electrode 112; second EFA stage 115 includes corona discharge electrode 113 and associated accelerating electrode 111. Both EFA stages and all the electrodes are shown schematically. Only one set of corona discharge and collecting electrodes are shown per stage for ease of illustration, although it is expected that each stage may include a large number of arrayed pairs of corona and accelerating electrodes. An important feature of EFA 100 is that the distance d_1 between the corona discharge electrode 106 and collector electrode 112 is comparable to the distance d_2 between collector electrode 112 and the corona discharge electrode 113 of the subsequent stage 115, *i.e.*, the closest distance between elements of adjacent stages is not much greater than the distance between electrodes within the same stage. Typically, the inter-stage distance d_2 between collector electrode 112 and corona discharge electrode 113 of the adjacent stage should be between 1.2 and 2.0 times that of the intra-stage spacing distance d_1 between corona discharge electrode 106 and collector electrode 112 (or spacing between corona discharge electrode 113, and collector electrode 111) within the same stage. Because of this consistent spacing, capacitance between electrodes 106 and 112 and between 106 and 113 are of the same order. Note that, in this arrangement, the capacitance coupling between corona discharge electrodes 106 and 113 may allow some parasitic current to flow between the electrodes. This parasitic current is of the same order of amplitude as a capacitive current between electrode pair 106 and 112. To decrease unnecessary current between electrodes 113 and 106, each should be

supplied with synchronized high voltage waveforms. In the embodiment depicted in Figure 1A both EFA stages are powered by a common power supply 105 *i.e.*, a power supply having a single voltage conversion circuit (*e.g.*, power transformer, rectifier, and filtering circuits, etc.) feeding both stages in parallel. This ensures that the voltage difference between electrodes 106 and 113 is maintained constant relative to electrodes 106 and 111 so that no or only a very small current flows between electrodes 106 and 113.

[0023] Figure 1B shows an alternate configuration of an EFA 101 including a pair of EFA stages 116 and 117 powered by separate power supplies 102 and 103, respectively. First EFA stage 116 includes corona discharge electrode 107 and collecting electrode 108 forming a pair of complementary electrodes within stage 116. Second EFA stage 117 includes corona discharge electrode 109 and collecting electrode 110 forming a second pair of complementary electrodes. Both EFA stage 116, 117 and all electrodes 107-110 are shown schematically.

[0024] First EFA stage 116 is powered by power supply 102 and second EFA stage 117 is powered by power supply 103. Both EFA stages as well as both power supplies 102 and 103 may be of the same design to simplify synchronization, although different designs may be used as appropriate to accommodate alternative arrangements. Power supplies 102 and 103 are synchronized by the control circuitry 104 to provide synchronized power outputs. Control circuitry ensures that both power supplies 102 and 103 generate synchronized and syn-phased output voltages that are substantially equal such that the potential difference between the electrodes 107 and 109 is maintained substantially constant (*e.g.*, has no or very small a.c. voltage component). (Note: While the term “synchronized” generally includes both

frequency and phase coincidence between signals, the phase-alignment requirement is further emphasized by use of the term “syn-phase” requiring that the signals be in-phase with each other at the relevant locations, *e.g.*, as applied to and as present at each stage.) Maintaining this potential difference constant (*i.e.*, minimizing or eliminating any a.c. voltage component) limits or eliminates any capacitive current flow between electrodes 107 and 109 to an acceptable value, *e.g.*, typically less than 1 mA and preferably less than 100 μ A.

[0025] The reduction of parasitic capacitive current between electrodes of adjacent EPA stages can be seen with reference to the waveforms depicted in Figures 2A and 2B. As seen in the Figure 2A, voltage V1 present on electrode 107 (Figure 1B) and voltage V2 present on electrode 109 are synchronized and syn-phased, but not necessarily equal in d.c. amplitude. Because of complete synchronization, the difference V1 – V2 between the voltages present on electrodes 107 and 109 is near constant representing only a d.c. offset value between the signals (*i.e.*, no a.c. component). A current I_c flowing through the capacitive coupling between electrode 107 and electrode 109 is proportioned to the time rate of change (dV/dt) of the voltage across this capacitance:

$$I_c = C * [d(V1 - V2)/dt].$$

[0026] It directly follows from this relationship that, if the voltage across any capacitance is held constant (*i.e.*, has no a.c. component), no current flows the path. On the other hand, even small voltage changes may create large capacitive current flows if the voltage changes quickly (*i.e.*, large $d(V1 - V2)/dt$). In order to avoid

excessive current flowing from the different electrodes of the neighboring EFA stages, voltages applied to the electrodes of these neighboring stages should be synchronized and syn-phased. For example, with reference to Figure 2B, corona voltage V1 and V2 are slightly out of synchronization resulting in a small a.c. voltage component in the difference, $d(V1 - V2)/dt$. This small a.c. voltage component results in a significant parasitic current I_c flowing between adjacent EFA stages. An embodiment of the present invention includes synchronization of power applied to all stages to avoid current flow between stages.

[0027] The closest spacing of electrodes of adjacent EFA stages may be approximated as follows. Note that a typical EFA operates efficiently over a rather narrow voltage range. The voltage V_c applied between the corona discharge and collecting electrodes of the same stage should exceed the so called corona onset voltage V_{onset} for proper operation. That is, when voltage V_c is less than V_{onset} , no corona discharge occurs and no air movement is generated. At the same time V_c should not exceed the dielectric breakdown voltage V_b so as to avoid arcing. Depending on electrodes geometry and other conditions, V_b may be more than twice as much as V_{onset} . For typical electrode configurations, the V_b/V_{onset} ratio is about 1.4 – 1.8 such that any particular corona discharge electrode should not be situated at a distance from a neighboring collecting electrode where it may generate a “back corona.” Therefore, the normalized distance a_{Nn} between closest electrodes of neighboring stages should be at least 1.2 times greater than the normalized distance “ a_{Nc} ” between the corona discharge and the collecting electrodes of the same stage and preferably not more than 2 times greater than distance “ a_{Nc} .” That is, electrodes of neighboring stages should be spaced so as to ensure that a voltage difference

between the electrodes is less than the corona onset voltage between any electrodes of the neighboring stages.

[0028] If the above stated conditions are not satisfied, a necessary consequence is that neighboring stages must be further and more widely spaced from each other than otherwise. Such increased spacing between stages results in several conditions adversely affecting air movement. For example, increased spacing between neighboring stages leads to a longer duct and, consequently, to greater resistance to airflow. The overall size and weight of the EFA is also increased. With synchronized and syn-phased HVPSs, these negative aspects are avoided by allowing for reduced spacing between HFA stages without reducing efficiency or increasing spark generation.

[0029] Referring to Figure 3, a two stage EFA 300 includes a pair of HVPSs 301 and 302 associated with respective first and second stages 312 and 313. Both stages are substantially identical and are supplied with electrical power by identical HVPSs 301 and 302. HVPSs 301 and 302 include respective pulse width modulation (PWM) controllers 304 and 305, power transistors 306 and 307, high voltage inductors 308 and 309 (*i.e.*, filtering chokes) and voltage doublers 301 and 302. HVPSs 320 and 321 provide power to respective EFA corona discharge electrodes of stages 312 and 313. As before, although EFA electrodes of stages 312 and 313 are diagrammatically depicted as single pairs of one corona discharge electrode and one accelerator (or attractor) electrode, each stage would typically include multiple pairs of electrodes configured in a two-dimensional array. PWM controllers 304, 305 generate (and provide at pin 7) high frequency pulses to the gates of respective power transistors 306 and 307. The frequency of these pulses is determined by respective

RC timing circuits including resistor 316 and capacitor 317, and resistor 318 and the capacitor 319. Ordinarily, slight differences between values of these components between stages results in slightly different operating frequencies of the two HVPS stages. However, even a slight variation in frequency leads to non-synchronous operation of stages 312 and 313 of EFA 300. Thus, to ensure the synchronous and syn-phased (*i.e.*, zero phase shift or difference) operation of power supplies 301 and 302, controller 305 is connected to receive a synchronization signal pulse from pin 1 of the PWM controller 304 via a synchronization input circuit including resistor 315 and capacitor 314. This arrangement synchronizes PWM controller 305 to PWM controller 304 so that both PWM controllers output voltage pulses that are both synchronous (same frequency) and syn-phased (same phase).

[0030] Figures 4A and 4B are cross-sectional views of two different arrangements of two-stage EFA devices. Although only two stages are illustrated, the principles and structure detailed is equally. With reference to Figure 4A, first EFA device 411 consists of two serial or tandem stages 414 and 415. First stage 414 contains a plurality of parallel corona discharge electrodes 401 aligned in a first vertical column and collecting electrodes 402 aligned in a second columns parallel to the column of corona discharge electrodes 401. All the electrodes are shown in cross-section longitudinally extending in to and out from the page. Corona discharge electrodes 401 may be in the form of conductive wires as illustrated, although other configurations may be used. Collecting electrodes 402 are shown horizontally elongate as conductive bars. Again, this is for purposes of illustration; other geometries and configurations may be implemented consistent with various embodiments of the invention. Second stage 415 similarly contains a column of

aligned corona discharge electrodes 403 (also shown as thin conductive wires extending perpendicular to the page) and collecting electrodes 404 (again as bars). All the electrodes are mounted within air duct 405. First and second stages 414 and 415 of EFA 411 are powered by respective separate HVPSs (not shown). The HVPSs are synchronized and syn-phased so the corona discharge electrodes 403 of second stage 415 may be placed at the closest possible normalized distance to collecting electrodes 402 of first stage 414 without adversely interacting and degrading EPA performance.

[0031] For the purposes of illustration, we assume that all voltages and components thereof (*e.g.*, a.c. and d.c.) applied to the electrodes of neighboring stages 414 and 415 are equal. It is further assumed that high voltages are applied to the corona discharge electrodes 401 and 403 and that the collecting electrodes 402 and 404 are grounded, *i.e.*, maintained at common ground potential relative to the high voltages applied to corona discharge electrodes 401 and 403. All electrodes are arranged in parallel vertical columns with corresponding electrodes of different stages horizontally aligned and vertically offset from the complementary electrode of its own stage in staggered columns. A normalized distance 410 between corona discharge electrodes 401 and the leading edges of the closest vertically adjacent collecting electrodes 402 is equal to $aN1$. Normalized distance $aN2$ (413) between corona electrodes 403 of the second stage and the trailing edges of collecting electrodes 402 of the first stage should be some distance $aN2$ greater than $aN1$, the actual distance depending of the specific voltage applied to the corona discharge electrodes. In any case, $aN2$ should be just greater than $aN1$, *i.e.*, be within a range of 1 to 2 times distance $aN1$ and, more preferably, 1.1 to 1.65 times $aN1$ and even more preferably

approximately 1.4 times a_{N1} . In particular, as depicted in Figure 4A, distance a_{N2} should be just greater than necessary to avoid a voltage between the corona onset voltage creating a current flow therebetween. Let us assume that this normalized “stant” distance a_{N2} is equal to $1.4 \times a_{N1}$. Then the horizontal distance 412 between neighboring stages is less than distance a_{N2} (413). As shown, intra-stage spacing is minimized when the same type of the electrodes of the neighboring stages are located in one plane 420 (as shown in Figure 4A). Plane 414 may be defined as a plane orthogonal to the plane containing the edges of the corona discharge electrodes (plane 417 in Figure 4A). If the same type electrodes of neighboring states are located in different but parallel planes, such as planes 421 and 422 (as shown in Figure 4B), the resultant minimal spacing distance between electrodes of adjacent EFA stages is equal to a_{N2} as shown by line 419. Note that the length of line 419 is the same as distance 413 (a_{N2}) and is greater than distance 412 so that inter-stage spacing is increased.

[0032] In summary, embodiments of the invention incorporate architectures satisfying one or more of three conditions in various combinations:

1. Electrodes of the neighboring EFA stages are powered with substantially the same voltage waveform, i.e., the potentials on the neighboring electrodes should have substantially same alternating components. Those alternating components should be close or identical in both magnitude and phase.
2. Neighboring EFA stages should be closely spaced, spacing between neighboring stages limited and determined by that distance which is just sufficient to avoid or minimize any corona discharge between the electrodes of the neighboring stages.
3. Same type electrodes of neighboring stages should be located

in the same plane that is orthogonal to the plane at which the electrodes (or electrodes leading edges) are located.

[0033] It should be noted and understood that all publications, patents and patent applications mentioned in this specification are indicative of the level of skill in the art to which the invention pertains. All publications, patents and patent applications are herein incorporated by reference to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated by reference in its entirety.